A MONOLITHIC CMOS-MEMS 3-AXIS ACCELEROMETER WITH A LOW-NOISE, LOW-POWER DUAL-CHOPPER AMPLIFIER

Hongwei Qu, Deyou Fang and Huikai Xie

Department of Electrical & Computer Engineering, University of Florida
Gainesville, Florida 32611-6200, USA

ABSTRACT

This paper reports the process development, interface circuit design and device characterization of a monolithically integrated 3-axis capacitive accelerometer with a single proof mass. An improved DRIE post-CMOS MEMS process has been developed, which provides robust single-crystal silicon structures in all three axes and greatly reduces undercut of comb fingers in dry release. A low-noise, low-power, dual-chopper amplifier is designed for each axis, which consumes only 1 mW power. With a 40dB on-chip amplification, the measured sensitivities of the lateral- and z-axis accelerometers are 560 mV/g and 320 mV/g, respectively, which can be decreased by simply decreasing the amplitude of the modulation signal. The over-all noise floors of the lateral- and z-axis are 12 $\mu\text{g}/\sqrt{\text{Hz}}$ and 110 $\mu\text{g}/\sqrt{\text{Hz}}$, respectively when tested around 200 Hz.

INTRODUCTION

Assembling single-axis accelerometers for 3-dimensional acceleration sensing drastically increases the packaging size and cost. Thus monolithic 3-axis accelerometers have drawn interests from both industry and universities [1-7]. Analog Devices, Inc. (ADI), Bosch, Freescale and ST Microelectronics have all launched their 3-axis accelerometers [1-4]. These commercially available 3-axis accelerometers are all based on thin-film microstructures and majority of them use hybrid packages, whose performances are normally limited by the structure thickness, residual stress and parasitics. The noise floors of most of these devices are on the order of a few hundreds $\mu\text{g}/\sqrt{\text{Hz}}$. Some bulk micromachined 3-axis accelerometers were demonstrated with higher resolutions [6, 7], but the micro-g resolutions were achieved at an expense of large device sizes. Furthermore, the wet etch based fabrication processes used in these bulk accelerometers require double-side alignment [6] and/or wafer bonding [7], resulting in high fabrication cost.

In order to achieve high resolution, small size and low cost simultaneously, a single-crystal silicon (SCS) based CMOS-MEMS 3-axis accelerometer with a single proof mass was developed [8]. But it has two drawbacks. First, although most of the sensing structure is made of single-crystal-silicon (SCS), the z-axis sensing employs Al/SiO₂ thin-film spring beams, which has poor temperature performance. Second, the silicon undercut for electrical isolation of substrate silicon also undercuts the silicon underneath comb fingers, which increases the comb-finger gap and in turn reduces the sensitivity and resolution. Recently, a new sensor design and fabrication process were proposed by Qu et al [9] to overcome the drawbacks in [8]. Better temperature performance was achieved by employing a torsional SCS-based z-axis spring; and the comb-finger undercut problem was much alleviated by performing the electrical isolation formation and the sensing structures etching separately.

However, there are still two significant issues in [9]. First, the overheating during the dry release step severely undercuts the sensing comb fingers and springs, increasing the comb-finger

gaps and even causing device failure. Second, the circuit noise still dominates the overall noise of the device.

In this paper, a further modified CMOS-MEMS process and a new amplifier design are used to resolve these two issues. The detailed characterization of fabricated 3-axis accelerometers is presented.

3-AXIS ACCELEROMETER AND CIRCUIT DESIGN

The 3-axis CMOS-MEMS accelerometer reported in this paper features a single proof mass for triple axes sensing, in which an imbalanced torsional z-axis sensing element is embedded in the lateral proof mass, as shown schematically in the 3-D model in Fig. 1. The lateral proof mass, along which the rotor comb-fingers are attached, is anchored to the substrate through two pairs of symmetric crab-leg SCS springs. The symmetric springs are flexible in both x- and y-axis, allowing the dual-axis in-plane sensing by two separate groups of orthogonally-oriented SCS comb-fingers. The differential capacitive sensing in z-axis is achieved by using the sidewall capacitance formed by the multiple metal layers in the thin-film portion of comb fingers [10]. The TSMC 4-metal 0.35 μm CMOS technology is used for CMOS fabrication through MOSIS. Three metal layers are used to form the z-sensing capacitors. By dividing the z-axis sensing capacitors into four groups and swapping the connections of the capacitors in upper and lower metal layers, fully differential sensing and offset cancellation can be realized [9]. Note that SCS is incorporated in both the torsional z-axis springs and sensing fingers for robust structures. The SCS in the z-axis sensing comb-fingers is purely for the purpose of mechanical support. In contrast, the SCS in the lateral-axes comb-fingers is used as both mechanical support and capacitor electrodes.

A SEM micrograph of a fabricated 3-axis accelerometer is shown with insets in Fig. 2, where the dimensions of the lateral and z-axis sensing elements are also given. The thickness of all the structures is 35 μm and the gap for all the comb-fingers is 2.1 μm . The length of the lateral- and z- axis sensing comb-fingers are 85 μm and 55 μm , respectively, both having the same width of 4.8 μm . The length and width of z-axis torsional mechanical springs are 400 μm and 4 μm , respectively. The crab-leg springs for lateral axes have the same length and width of 320 μm and 5 μm in both directions.

Figure 1. Schematic 3-D model of the 3-axis accelerometer. Electrical isolation structures are not shown.

Figure 2. SEM photograph of the sensing element of the fabricated CMOS-MEMS 3-axis accelerometer. The insets show front and backside of the electrical isolation structures.

With the above design parameters, the calculated sensitivity of the lateral axes and z-axis are 4.5 mV/g and 2.3 mV/g, respectively with a 1.5 V modulation.

A two-stage dual-chopper amplifier (DCA) is integrated with the 3-axis accelerometer for each axis as the continuous-time readout circuit. A total gain of 40dB is designed. Fig. 3 shows the DCA architecture which employs two modulation clocks (1 MHz and 20 kHz respectively) to achieve low noise and low power consumption simultaneously [11].

Figure 3. Diagram of the interface circuit.

The post-CMOS microfabrication reported in [9] improves the device performance by reducing the undercut on comb fingers and mechanical springs. This is accomplished by performing the electrical isolation etch and the final release of comb fingers and mechanical springs separately. Top metal layer (M4) is only used to pattern the electrical isolation structures. After the electrical isolation trenches are formed, as shown in the insets of Fig. 2, M4 is removed by wet or plasma aluminum etch to expose the patterns of other structures of the accelerometer.

Some negative effects caused by the two-step etch process were observed. The most significant one is the rapid silicon undercut of comb fingers and mechanical springs due to the overheating of these fine structures during the plasma etch. This undercut happens even within a very short over-etch after the accelerometer is released. The reason for the severe undercut is the reduced thermal conductance from the comb fingers to the substrate. The heat generated from chemical reaction and ion bombardment in silicon DRIE can not be dissipated effectively, which consequently raises the temperature of the suspended microstructures. This positive feedback eventually leads to high etching rate and the comb fingers will be undercut very quickly. The same effect was also observed on the z-axis sensing element where the heat can only be transferred through the two long torsional springs.

Precise etching end-point detection is an effective method to avoid the over etch [12]. However, this requires additional sophisticated instruments on the current DRIE system and the detection accuracy is limited due to a wide range of structure complexities and opening sizes. In this work, we demonstrated a modified process, which effectively solves the thermally related comb-finger undercut.

The process flow is illustrated in Fig. 4. There is only one slight modification to the CMOS-MEMS process used in [9]. After the backside etch that produces a silicon membrane and defines the structure thickness (Fig. 4(a)), a thick sacrificial photoresist layer ($\sim 50\mu\text{m}$) is applied on the back of the silicon membrane (Fig. 4(b)). After the isolation etching is completed (Fig. 4(c)-4(d)), this

Figure 4. Post-CMOS microfabrication process flow. (a) Backside etch. (b) Backside photoresist coating followed by front side anisotropic SiO_2 etch. (c) Top Al etch. (d) Deep Si etch and undercut to form isolation structures. (e) Anisotropic SiO_2 etch and DRIE Si etch for comb fingers and mechanical springs. (f) Photoresist ashing for final release.

Figure 5. (a) By using backside photoresist coating, the release of the sensing fingers are well controlled with slight footing effect. (b) Without backside photoresist coating, some comb fingers are etched away in a similar release etch.

photoresist layer functions as a thermal path during the DRIE silicon etch that forms the entire microstructure (Fig. 4(e)). Finally, the photoresist is removed by oxygen plasma ashing to release the device (Fig. 4(f)). In Fig. 5, a comparison is made between sensing comb fingers fabricated with and without backside photoresist coating. The undercut of the silicon on comb fingers is greatly reduced and the finger damage is completely avoided by using the modified process (Fig. 5(a)). Furthermore, the photoresist layer helps reducing the backside contamination caused by back scattering. In contrast, without the photoresist layer as thermal path, electrical isolation trenches greatly reduce thermal flow from comb fingers to substrate. Consequently comb fingers are over heated and seriously undercut (Fig. 5(b)).

It should be pointed out that the thermal effect and the modified process described above are valid to many other MEMS devices with structures similar to this 3-axis accelerometer. A proper device design also helps in reducing the thermal problem described above. By considering the aspect-ratio dependent etching effect (ARDE), we can design the device in such a way that the etch-through sequence for different structures can be well controlled.

EXPERIMENTAL RESULTS

Fig. 6 is the photograph of a wire bonded die showing the locations of the 3-axis sensor and interface circuits. A dummy on-chip interface circuit was tested with an overall gain of 40 dB and a 16 nV/ $\sqrt{\text{Hz}}$ electronic noise floor was measured.

The sensitivities in the lateral axes and z axis were measured as 560 mV/g and 320 mV/g, respectively, at a 1.5 V modulation signal using a Piezotronics shaker which provides standard 1-g acceleration at 159.1 Hz. An impulse response test showed that the resonant frequencies for the lateral axes and z axis are 1.5 kHz and 450 Hz, respectively. These frequencies are about 15% lower than the simulated results, reflecting a remaining slight undercut to the mechanical springs in the plasma etch process. Due to the asymmetry of the z-axis proof mass, the z-axis sensing element has relatively high cross-axis sensitivities which were measured to be 2.1% from the x-axis and 4.7% from the y-axis, as shown in Fig. 7. The noise measurement was conducted using a LDS shake table and SRS network spectrum analyzer. The spectral response of the z-axis output at a 200 Hz, 0.5-g external

Figure 6. Photograph of the wire bonded die.

Figure 7. Static test results of the z- and y- axis using a precision rotary stage.

acceleration is shown in Fig. 8. The overall noise floor of the z element is 110 $\mu\text{g}/\sqrt{\text{Hz}}$. Although both x- and y-axis have the same number of identical sensing comb-fingers, there is a slight sensitivity difference between these two lateral axes due to the arrangement of the mechanical springs. The spectrum of y-axis output under a 200 Hz, 0.05-g acceleration is shown in Fig. 9. An overall noise floor of 12 $\mu\text{g}/\sqrt{\text{Hz}}$ is demonstrated.

The temperature coefficient of sensing capacitance originates from the thermal-induced curling of the thin-film electrical isolation beams, in which aluminum and SiO_2 have different temperature coefficient of expansion. Therefore, by measuring the temperature coefficient of the comb finger curling, the temperature performance of the sensor can be extrapolated. In experiment, the PLCC-52 sensor package was heated by a band heater taped on the back of the package, and the sensor temperature was measured by a spot thermocouple. The vertical curling of the sensing comb fingers was measured in a temperature range from room temperature to 96°C, using a Wyko surface optical profilometer. A maximum net negative 0.533 μm curling at the free end of the comb-fingers was measured in the above temperature range. Since the sensor structure thickness is 35 μm , the corresponding change of the electrode engaged area is approximately 0.23%. Based on these measurements, a positive $3.04 \times 10^{-4}/^\circ\text{C}$ temperature coefficient of sensitivity (TCS) of the lateral sensor was extrapolated. Due to the complete SCS structure,

Figure 8. The spectrum of the z-axis output under 0.5g at 200 Hz (RBW = 1Hz).

no apparent temperature-induced structure curling was observed on the z-axis sensing element. An overall sensor TCS of approximately 0.285%/°C was measured, which is mainly caused by the gain drifting of the first open-loop amplification stage of the on-chip amplifier. This is verified by circuit simulation, and a temperature insensitive amplifier is under design.

The measured performance is further summarized in Table 1. As a comparison, the performance of ADXL330, a 3-axis accelerometer from ADI, is included.

Table 1. Performance summary of the reported device and a comparison with ADXL330 from ADI [1].

Parameters	Measured Values	
	This work	ADXL330
Chip size (mm × mm)	3×3	4×4 (package)
Lateral axes sensitivity (mV/g)	560	300
Z axis sensitivity (mV/g)	320	300
Circuit noise floor (nV/√Hz)	16	-
Power consumption of each axis (mW)	1	0.64~1.15
Lateral axes noise floor (µg/√Hz)	12	170
Z axis noise floor (µg/√Hz)	110	350

CONCLUSION

A 3-axis CMOS-MEMS accelerometer with a single proof mass has been demonstrated in this work. The single-crystal silicon incorporated in the device ensures robust sensor structures and high resolution. Low-power consumption (1 mW for each sensing axis) and low-noise floors in all three axes are achieved simultaneously with a compact device size. Compared to the previous processes, this modified post-CMOS microfabrication process has much larger process tolerances by providing additional thermal path to the suspended microstructures in plasma etching processes. Though only photoresist was used in this work, there exist many other more suitable materials for the additional heat dissipation. This method can be widely used in the micromachining of MEMS devices with similar suspended structures. Due to its small size, low power consumption and high resolution, this 3-axis accelerometer has a variety of applications including health monitoring, video games and infrastructure securities.

Figure 9. The spectrum of the y-axis output under 0.05g at 200 Hz (RBW = 1Hz).

ACKNOWLEDGEMENT

This project is partially supported by the UCF-UF Space Research Initiative and University of Florida Startup Fund. The CMOS chip fabrication was supported by MOSIS through its Educational Program.

REFERENCES

- [1] Analog Devices, Inc., "ADXL330 low-power, iMEMS 3-axis accelerometer", Datasheet Rev. PrA., Oct. 2005.
- [2] Bosch Sensortech, "SMB360 triaxial acceleration sensor", Datasheet Rev. 1, Nov. 2005.
- [3] Freescale Semiconductor, "MMA7260Q 3-axis accelerometer", Datasheet Rev. 2, Feb. 2006.
- [4] ST Microelectronics, "LIS3L02AQ3 MEMS linear inertial sensor", Datasheet Rev. 2, May 2005.
- [5] M. Lemkin and B. E. Boser, "A three-axis micromachined accelerometer with a CMOS position-sense interface and digital offset-trim electronics," *IEEE J. of Solid-State Circuits*, vol. **34**, No. **4**, pp. 456-468, 1999.
- [6] J. Chae, H. Kulah and K. Najafi, "A monolithic three-axis micro-g micromachined silicon capacitive accelerometer," *J. of MEMS*, vol. **14**, pp. 235-242, 2005.
- [7] H. Takao, H. Fukumoto and M. Ishida, "A CMOS integrated three-axis accelerometer fabricated with commercial submicrometer CMOS technology and bulk-micromachining," *IEEE Trans. on Elec. Devices*, vol. **48**, pp. 1961-1968, 2001.
- [8] H. Xie, Z. Pan, W. Frey, and G. Fedder, "Design and Fabrication of an Integrated CMOS-MEMS 3-Axis Accelerometer," *The 2003 Nanotechnology Conference*, 2003.
- [9] H. Qu, D. Fang, and H. Xie, "A single-crystal silicon 3-axis CMOS-MEMS accelerometer," *Proceedings of IEEE Sensors 2004*, vol. **2**, pp.661-664, Oct. 24-27, 2004, Vienna, Austria.
- [10] H. Xie, and G.K. Fedder, "Vertical Comb-finger Capacitive Actuation and Sensing for CMOS-MEMS," *Sensors & Actuators, A*, Vol. **95** (2002), pp. 212-221.
- [11] D. Fang, H. Qu and H. Xie, "A 1mW dual-chopper amplifier for a 50 µg/√Hz monolithic CMOS-MEMS capacitive accelerometer", to be presented at the *2006 Symp. on VLSI Circuit*, Jun. 15-17, 2006, Honolulu, Hawaii.
- [12] Z. Wan, J. Liu, and H. H. Lamb, "Electron cyclotron resonance plasma reactor for SiO₂ etching: Process diagnostics, end-point detection, and surface characterization," *J. of Vacc. Sci. & Tech.: A*, vol. **13**, pp. 2035-2043, 1995.